UNITED STATES
DEPARTMENT OF THE INTERIOR
BUREAU OF RECLAMATION

STILLING BASIN PERFORMANCE STUDIES
AN AID IN DETERMINING RIPRAP SIZES

Hydraulic Laboratory Report No. Hyd-409

DIVISION OF ENGINEERING LABORATORIES

COMMISSIONER'S OFFICE
DENVER, COLORADO

February 23, 1956

ERRATA SHEET FOR HYD-409
Stilling Basin Performance Studies--
an Aid in Determining Riprap Sizes

On page 5, 3rd paragraph, the statement, "Mavis and Laushey proposed an identical equation. . ." should read, "Mavis and Laushey proposed an equation. ."

The equation should read,

$$V_b = \frac{1}{2} \sqrt{d_1} \sqrt{s-1}$$

and the identification,

"d_1=diameter of particle in millimeters," should be added.

CONTENTS

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Commissioner's Office--Denver
Division of Engineering Laboratories
Hydraulic Laboratory Branch
Hydraulic Structures and Equipment Section
Denver, Colorado
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Laboratory Report No. Hyd-409
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Subject: Stilling basin performance studies--An aid in determining riprap sizes

INTRODUCTION AND SUMMARY

Part of the research program of the Hydraulic Laboratory has been the development of an impact-type stilling basin for use on relatively small canal structures. This basin, originally developed for structures on the Franklin Canal, Missouri River Basin Project, Bostwick Division, has been generalized through the cooperation of the Canals Branch engineers for use on other canal systems, as discussed in Hydraulic Laboratory Report No. Hyd-399, Stilling Basin VI. As a result, well over 100 basins of this type have been designed and a considerable number have already been built. Since the design is novel, and since a great many sizes of structures have been utilized, operating experiences with the structures, compared to the predictions made from the hydraulic model tests, are of interest. However, only a few basins are known to have operated, and only two are known to have been subjected to a major test.

The general design rules developed for Stilling Basin VI cover the determination of the structure's size and dimensions, and the general method of placement of riprap, but do not indicate the size of riprap to be used. Operation of the two prototype basins discussed in this report provided an opportunity to study the riprap problem. As a result, tentative recommendations for the minimum size of riprap to be used on these or other structures can now be presented.

REFERENCE MATERIAL

Data and photographs of the prototype performance of the two stilling structures were taken from the report "Structural Behavior of Picacho Arroyo Control Works, Storm Runoff, August 20 and 21, 1954," by John B. Delaney, September 16, 1954. This report is available from the

Communications and Records Section, File No. 500RG, Commissioner's Office, Denver. Data and photographs of the model performance were taken from Hydraulic Laboratory Reports No. Hyd-398, -399, and from unpublished data in the laboratory files. The control structures discussed are part of the Picacho Arroyo System, Rio Grande Project, New Mexico-Texas, and are described in Specifications Nos. DC-3856, DC-3934, and DC-4002, Bureau of Reclamation.

PROTOTYPE STRUCTURES

The Picacho South Dam outlet works structure, designed for a maximum discharge of 165 second-feet, is shown on Figure 1. The dimensions agree closely with those recommended from the hydraulic model tests, Figures 2 and 3. (Interpolate between 151 and 191 in Column 3 of Figure 3.) The Picacho North Branch Dam outlet works, Figure 4, designed for a maximum discharge of 275 second-feet, was also constructed according to the hydraulic model test recommendations. (Compare dimensions in Figure 4 with values interpolated between 236 and 339 in Column 3 of Figure 3.) The design criteria for structures of this type are discussed in Hydraulic Laboratory Report No. Hyd-399.

PROTOTYPE PERFORMANCE

Rain over Picacho watershed of about 0.5 inch produced the first major run of the control works. Flow through the two ungated detention dams, known as the North and South Dams, started about 5 p.m. on August 20 and continued for almost 24 hours. Flow from the detention dams was discharged through the impact-type stilling structures described above. The combined total discharge at both dams was in excess of 400 acre-feet. Following the storm, high water elevations were obtained in the ponding basins behind the dams, and from design data the following information is indicated:

	North Dam	South Dam
Maximum water surface elevation, ft	3938.0	3941.0
Acre-feet impounded on August 20, 1954	125	110
High water elevation on August 20, 1954, ft	3920.3	3931.4
Intake elevation, ft	3911.0	3921.0
Head on intake on August 20, 1954, ft	9.3	10.4
Maximum head on intake, ft	27.0	20.0
Maximum discharge in second-feet	275	165
High discharge on August 20, 1954, sec-ft	210	130
Percent of maximum discharge on August 20	80	80

	North Dam	South Dam
Elevation of stilling basin floor, ft	3895.71	3912.92
Maximum head on outlet, ft	42.29	28.08
Head on August 20, 1954, ft	24.59	18.48
Maximum estimated velocity, ft/sec	48.0	39.0
Maximum estimated velocity on August 20, 1954	37.0	31.8
Critical velocity over end sill on August 20, ft/sec	7.6	6.9
Velocity striking riprap August 20, ft/sec	12±	5±

The North and South Dams control facilities provided flood protection up to the degree for which they were constructed. Flow through the stilling basins was observed to be satisfactory in that the basins dissipated the energy of the incoming flow as expected and discharged the flow into the downstream channel in a well-distributed pattern. Flow leaving the North Dam outlet washed out the riprap below the stilling basin, however, and undercut the structure to a depth of about 2 feet. A detailed account of the performance and scour-preventive measures are discussed in the following sections.

MODEL-PROTOTYPE COMPARISON

The North Dam and the outlet works structure are shown in Figure 5. Operation at 80 percent of maximum discharge, 210 second-feet, is shown in Figure 6 along with the model operating under very similar conditions. Figure 7 shows the erosion below the prototype after the August 20 flood and the erosion in the model for the maximum discharge. Figure 8 shows the performance of the South Dam outlet structure at 80 percent of maximum discharge, 130 second-feet, and the model operating under similar conditions. Figure 9 shows the channel below the South Dam outlet.

From the photographs it is apparent that the agreement between model and prototype is excellent. The photographs show the remarkable similarity in the model and prototype flow patterns leaving the outlet structures. Closer inspection is necessary, however, to show similarity with regard to scour below the model and prototype structures. The model photograph, Figure 7, shows the scour depth and extent when there was no riprap protection provided in the channel. The pea-gravel used in the model was considered to be an erodible bed. The contours, visible as white lines, show that the erosion depth was 19/26 of the sill height below apron elevation. Since the prototype sill height is 31.5 inches, scour depth in the prototype without riprap protection, should be about 23 inches below apron elevation. This compares very favorably with the 2 feet measured in the prototype. The more general erosion which occurred in the prototype is probably due to the higher velocity entering the prototype stilling basin. The estimated velocity (based on calculations) of 37 feet per second is greater than the upper velocity limit, 30 feet per second, used in the model tests and recommended for the upper limit in prototype structures of this type. Larger riprap would have prevented the erosion.

According to Specifications No. DC-3856 the riprap below the outlet "* * * shall consist of durable rock fragments reasonably graded in size * * *" from 1/8 cubic yard to 1/10 cubic foot. The individual rocks, therefore, would vary from about 18-inch cubes to 5-1/2-inch cubes, or in weight, from about 500 pounds to 15 pounds. Although it is impossible from the photograph of Figure 7 to determine the size of riprap in the channel at the start of the run, the bank riprap indicates that there were very few rock pieces of the 500-pound size. The few remaining pieces near the man at the right seem to be in the upper size range and apparently these did not move. In the hydraulic model tests made to develop this basin, riprap corresponding to 9- to 18-inch cubes did not show excessive movement of the rock mass, Figure 10, but did show some erosion downstream from the end sill.

As a further check on the riprap size necessary to withstand the erosive forces the curve of Figure 11 indicates the velocity at which individual stones begin to move. These data apply strictly to uniform channels having uniform velocity distribution; the velocity at which the stones begin to move is the bottom velocity in the channel, not the average velocity. Using this graph for the case at hand, the critical stone size is about 20 inches. This checks the equivalent 9- to 18-inch stone size, used in the model tests, to a reasonable degree since some of the model riprap did move.

On the basis of the above discussion it appears that a stone size of 18- to 20-inch minimum would have been required to prevent movement of the riprap below the North Dam outlet. To withstand the maximum velocity to be expected when the structure is subjected to full head and discharge conditions, larger stones would be required, perhaps 24-inch minimum.

In contrast to the situation at the North Dam the riprap at the outlet of the South Dam was relatively undisturbed, Figure 9. No mention of damage or recommendation for repairs at the South Dam outlet is given by Mr. Delaney in his report. Flow conditions below the South Dam outlet are shown in Figure 8.

The velocity over the end sill of the South Dam basin is much lower than at the North Dam, being only about 5 feet per second. According to the curve of Figure 11, the riprap size required would be about 4 inches. Since the riprap sizes, given in Specifications No. DC-4002 for the South Dam outlet are the same as for the North Dam outlet, the stone size in this case was sufficiently large to resist movement.

RIPRAP SIZE DETERMINATION

A suggested minimum size for riprap is given by the curve in Figure 11. The curve indicates, over most of its range, that doubling the flow velocity leaving a structure makes it necessary to provide riprap about 4 times larger in nominal diameter or 16 times larger in volume or weight.

The lower portion of the curve is an average of data reported by Du Buat in 1786, Bouniceau in 1845, Blackwell in 1857, Sainjon in 1871, Suchier in 1874, and Gilbert in 1914. It checks well with results of tests made at the State University of Iowa by Chitty Ho, Yun-Cheng Tu, Te Yun Liu, and Edward Soucek. The data were assembled and discussed in a paper "A Reappraisal of the Beginnings of Bed Movement-Competent Velocity" by F. T. Mavis and L. M. Laushey, for the International Association for Hydraulic Structures Research, 1948, Stockholm, Sweden. In a thesis by N. K. Berry, University of Colorado, 1948, an identical curve was determined and an equation for it presented.

$$V_b = 2.57 \sqrt{d}$$

where

V_b = bottom velocity in channel in feet per second
d = diameter of particle in inches

In this case the specific gravity of the particle is 2.65.

Mavis and Laushey proposed an identical equation for use with particles of any specific gravity

$$V_b = 1/2 \sqrt{d} \sqrt{s - 1}$$

where

s = specific gravity of the particle

Rationalization of all the known factors indicates that the curve may be directly applicable for the determination of riprap sizes, particularly since it indicates larger stone sizes for the North Dam outlet than were used and agrees reasonably well with general laboratory experience. Until more data and experience with this curve are available, the velocity, determined by dividing discharge by flow area at the end sill, may be used. Until the interlocking effect of the rock pieces can be determined, most of the riprap should consist of the size indicated by the curve.

It should be noted in Figure 6 that the tail water is low with respect to the stilling basin. Therefore, the velocity over the end sill is considerably lower than the velocity striking the riprap. For the North Dam basin having a sill length of 15.5 feet, a critical depth of 1.5 feet over the end sill and a discharge of 210 second-feet, the critical velocity would be 7.6 feet per second, requiring riprap, Figure 11, about 9 inches in diameter. Further acceleration of the flow by a drop from the end sill to the tail water surface of 2 feet, Figure 6, would result in a velocity of about 14 feet per second, requiring riprap about 30 inches in diameter. Thus, the importance of matching the basin elevation to the probable tail water elevation is evident. In the case of the North Dam basin, however, the tail water elevation was, no doubt, higher before the riprap was lost.

CONCLUSIONS

The passage of the flood of August 20 through the two outlet works structures of the Picacho Arroyo Control indicates that the prototype performance was as predicted by the hydraulic model tests. These stilling basins are of the type "Stilling Basin VI," described and generalized for simple design and construction in Hydraulic Laboratory Report No. Hyd-399. Despite the fact that the general design rules limit the incoming velocity to 30 feet per second, the North and South Dams structures performed very well for velocities computed to be about 37 and 32 feet per second, respectively, with discharges equal to 80 percent of design capacity. The only adverse comment regarding these structures was the loss of the riprap below the North Dam outlet works.

The outlet works structures at the North and South Dams appear, off hand, to be of about the same general size, both in physical dimensions and in the quantity of water to be handled. On this basis, apparently, riprap sizes were specified to consist of material from 1/8 cubic yard to 1/10 cubic foot, for both structures. On the North Dam outlet works this material was entirely removed from the channel bottom by outflow having a velocity of about 12 feet per second. Below the South Dam outlet works the same material remained in place with an outflow velocity of about 5 feet per second, considerably lower than at the North Dam. It is therefore evident that the minimum stone sizes are critical with respect to the velocity below the structure.

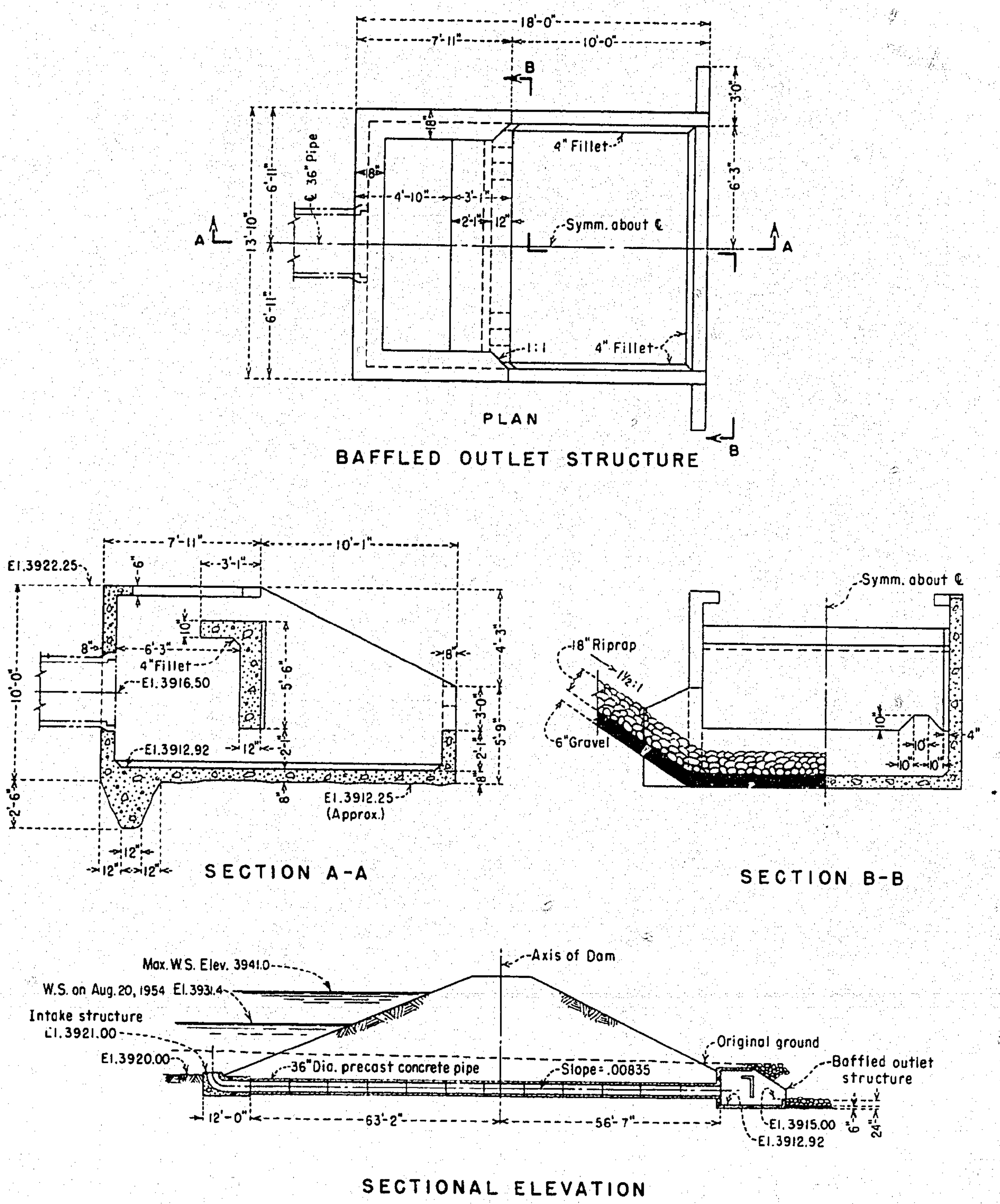
RECOMMENDATIONS

It is recommended that riprap sizes for future projects be specified using Figure 11 as a guide. It is felt that this curve, even though it has not been fully proven, will provide a starting point for development of an accurate method to determine minimum stone sizes. The curve indicates, over most of its range, that doubling the flow velocity leaving a structure makes it necessary to provide riprap about 4 times larger in nominal diameter or 16 times larger in volume or weight. These factors alone provide a basis for thought in providing riprap material.

Based on the data and discussions presented in this report it is recommended that the riprap sizes given below be used downstream from impact-type stilling basins, Figures 2 and 3. Column 1 is identical with Column 3 of Figure 3. Column 2 gives the minimum size stone when there is no drop in water surface elevation from basin to tail water.

(1) Maximum discharge, cfs	(2) Minimum stone size, inches
21	4.0
38	7.0
59	8.5
85	9.0
115	9.5
151	10.5
191	12.0
236	13.0
339	14.0

It is also recommended that laboratory and field tests be requested to confirm the accuracy of the velocity versus stone size relation given in Figure 11.

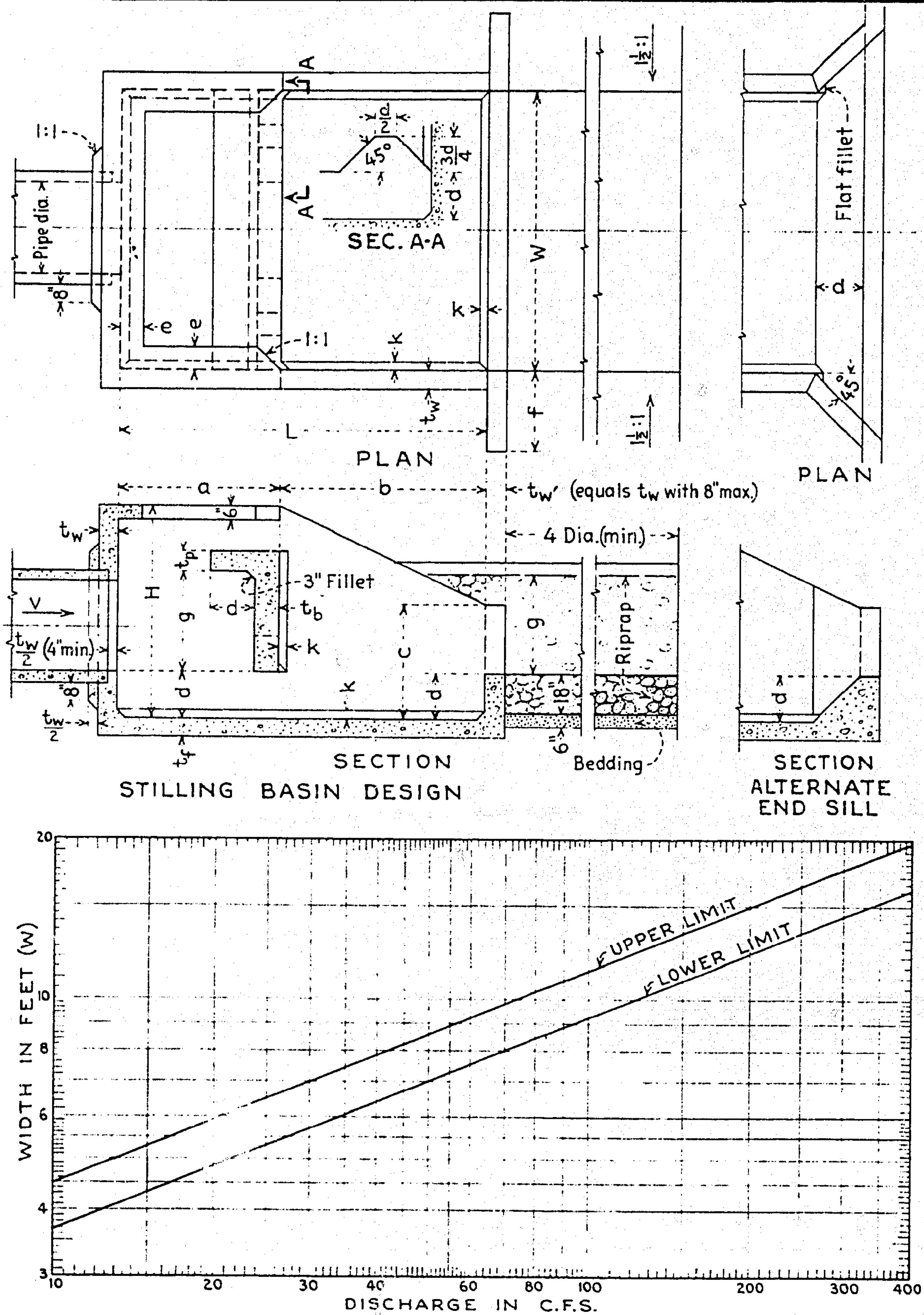


RIO GRANDE PROJECT
LAS CRUCES DIVISION – NEW MEXICO

PICACHO SOUTH DAM

OUTLET WORKS

FIGURE 2



DISCHARGE LIMITS

IMPACT TYPE ENERGY DISSIPATOR
(BASIN VI)

Table 11

STILLING BASIN DIMENSIONS
Impact-type Energy Dissipator
(Basin VI)

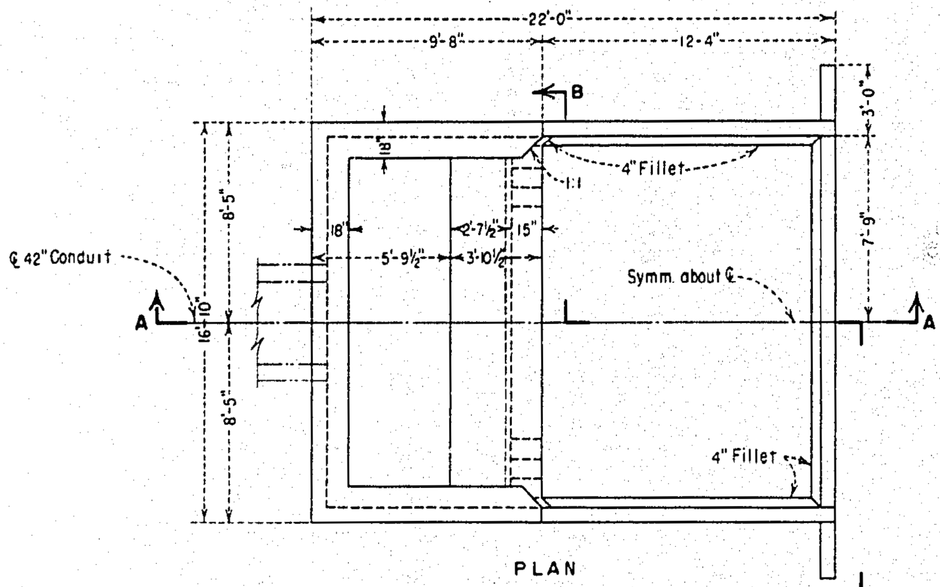
Suggested pipe size*		Maximum discharge	Feet and inches										Inches				
Dia in. (1)	Area (sq ft) (2)	Q (3)	W (4)	H (5)	L (6)	a (7)	b (8)	c (9)	d (10)	e (11)	f (12)	g (13)	t_w (14)	t_f (15)	t_b (16)	t_p (17)	K (18)
18	1.7672	21**	5-6	4-3	7-4	3-3	4-1	2-4	0-11	0-6	1-6	2-1	6	6-1/2	6	6	3
24	3.1416	38	6-9	5-3	9-0	3-11	5-1	2-10	1-2	0-6	2-0	2-6	6	6-1/2	6	6	3
30	4.9087	59	8-0	6-3	10-8	4-7	6-1	3-4	1-4	0-8	2-6	3-0	6	6-1/2	7	7	3
36	7.0686	85	9-3	7-3	12-4	5-3	7-1	3-10	1-7	0-8	3-0	3-6	7	7-1/2	8	8	3
42	9.6211	115	10-6	8-0	14-0	6-0	8-0	4-5	1-9	0-10	3-0	3-11	8	8-1/2	9	8	4
48	12.5664	151	11-9	9-0	15-8	6-9	8-11	4-11	2-0	0-10	3-0	4-5	9	9-1/2	10	8	4
54	15.9043	191	13-0	9-9	17-4	7-4	10-0	5-5	2-2	1-0	3-0	4-11	10	10-1/2	10	8	4
60	19.6350	236	14-3	10-9	19-0	8-0	11-0	5-11	2-5	1-0	3-0	5-4	11	11-1/2	11	8	6
72	28.2743	339	16-6	12-3	22-0	9-3	12-9	6-11	2-9	1-3	3-0	6-2	12	12-1/2	12	8	6

*Suggested pipe will run full when velocity is 12 feet per second or half full when velocity is 24 feet per second. Size may be modified for other velocities by Q = AV, but relation between Q and basin dimensions shown must be maintained.

**For discharges less than 21 second-feet, obtain basin width from curve of Figure 2. Other dimensions proportional to W; $H = \frac{3W}{4}$, $L = \frac{4W}{3}$, $d = \frac{W}{6}$, etc.

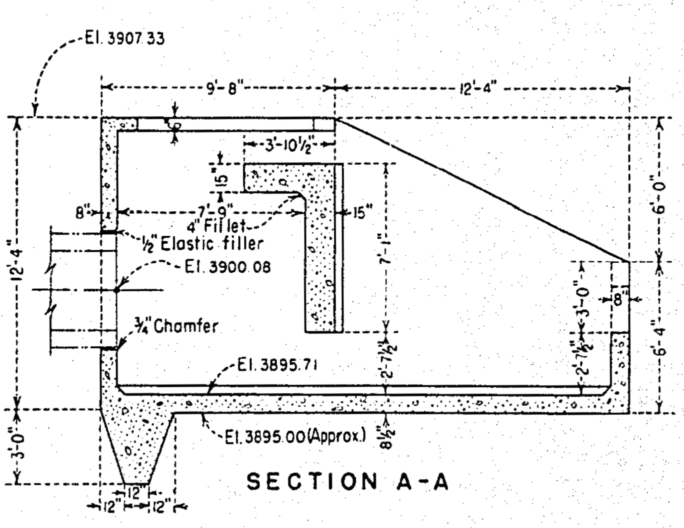
FIGURE 3

FIGURE 4

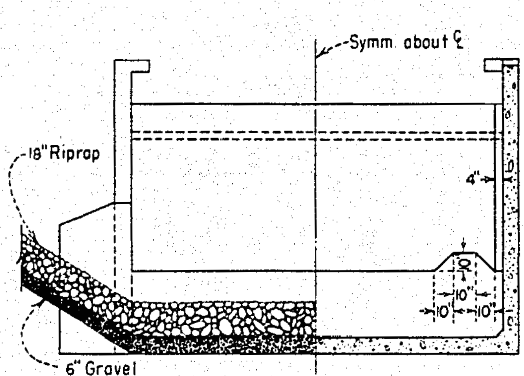


PLAN

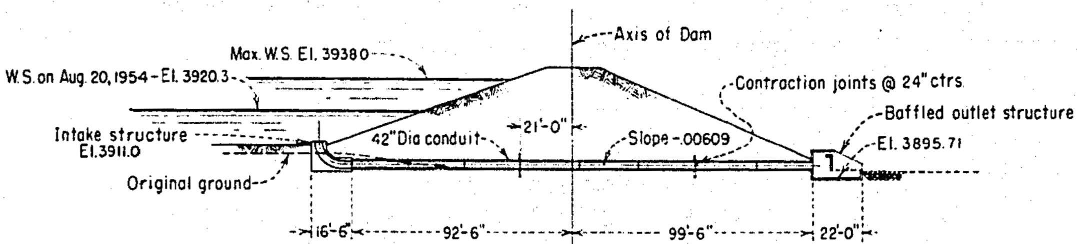
BAFFLED OUTLET STRUCTURE



SECTION A-A



SECTION B-B



SECTIONAL ELEVATION

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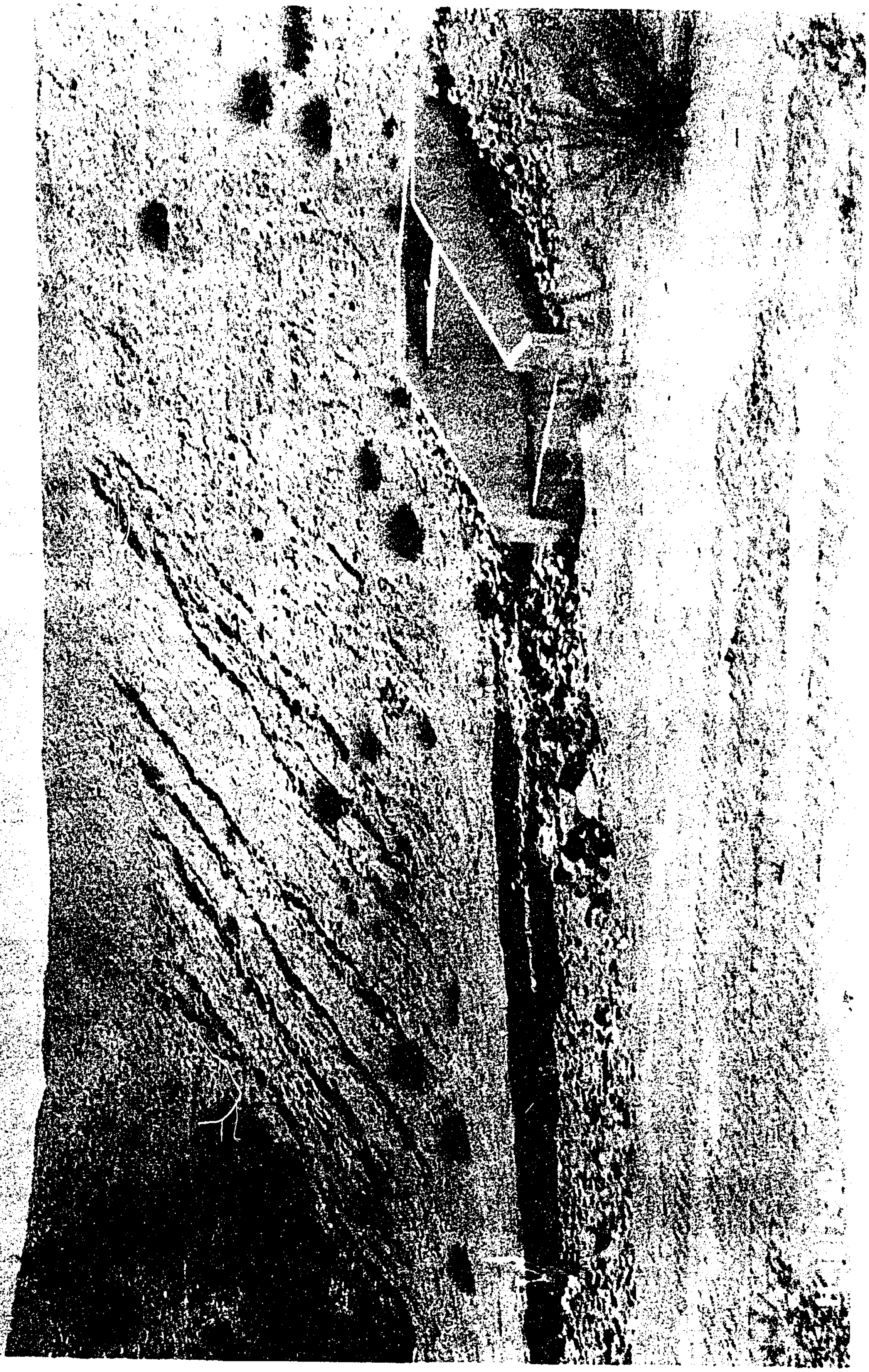
PICACHO ARROYO CONTROL

NORTH BRANCH DAM

OUTLET WORKS

546

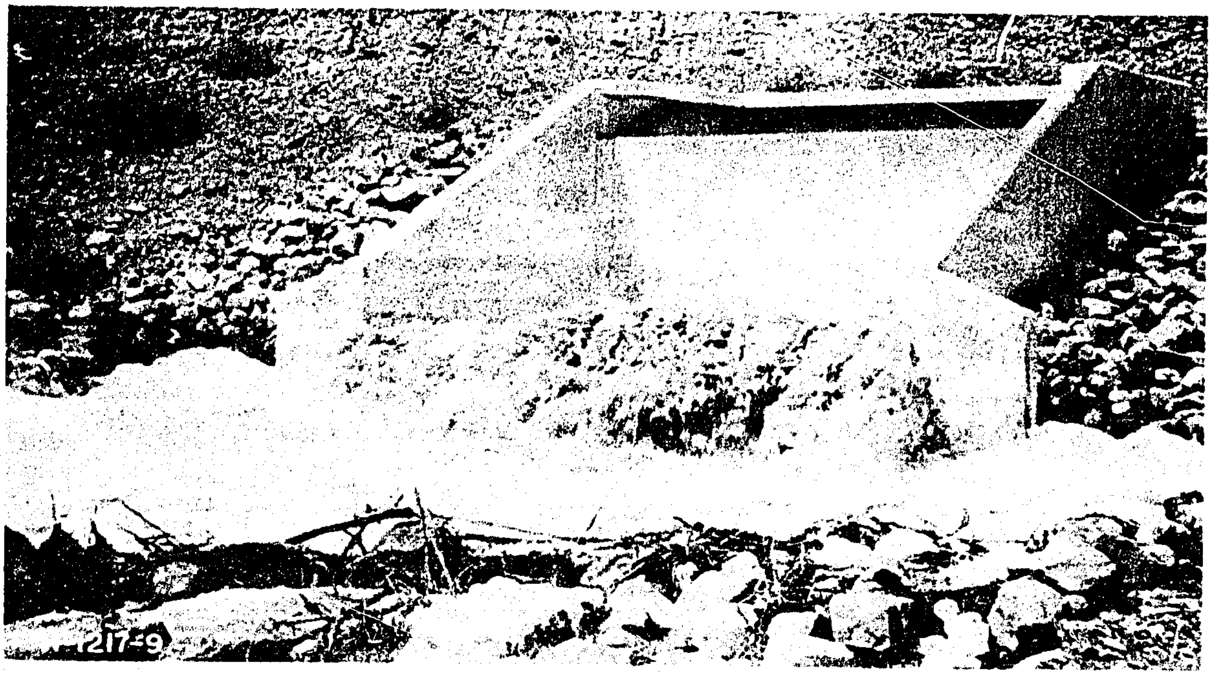
FIGURE 5



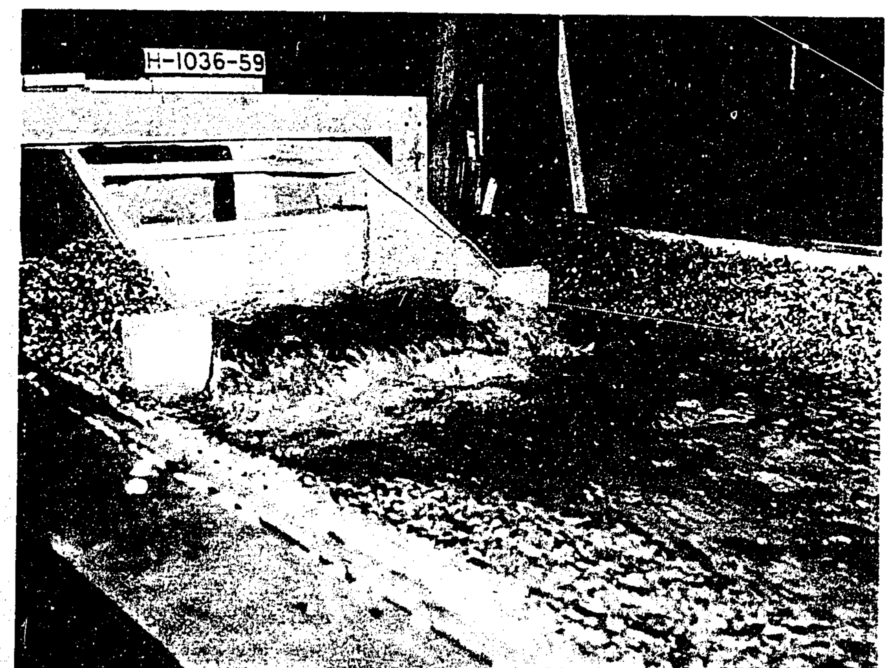
Impact-type stilling basin structure - following flood of August 20, 1954. North Branch Dam in background.

PICACHO ARROYO CONTROL
NORTH BRANCH DAM

FIGURE 6



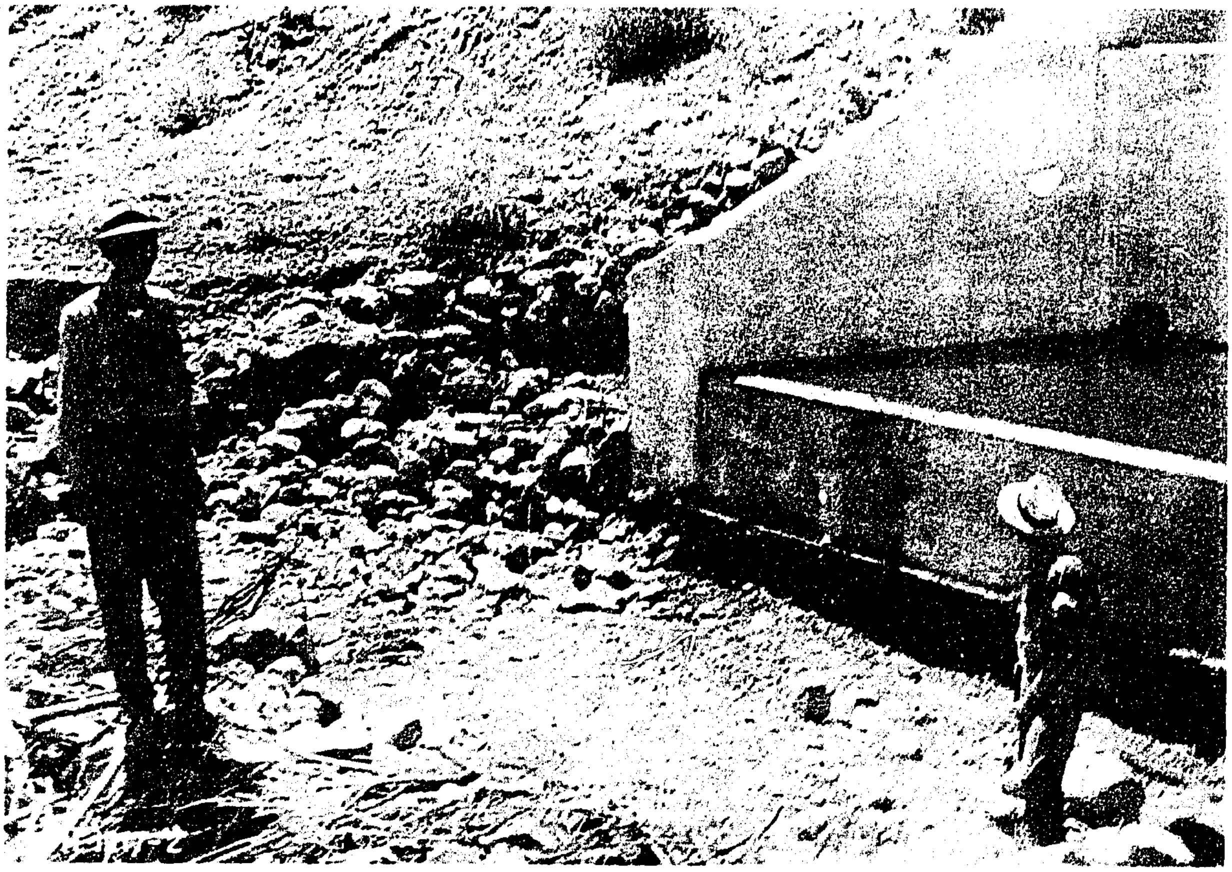
North Branch Dam outlet works structure discharging
210 second-feet (80 percent of maximum).



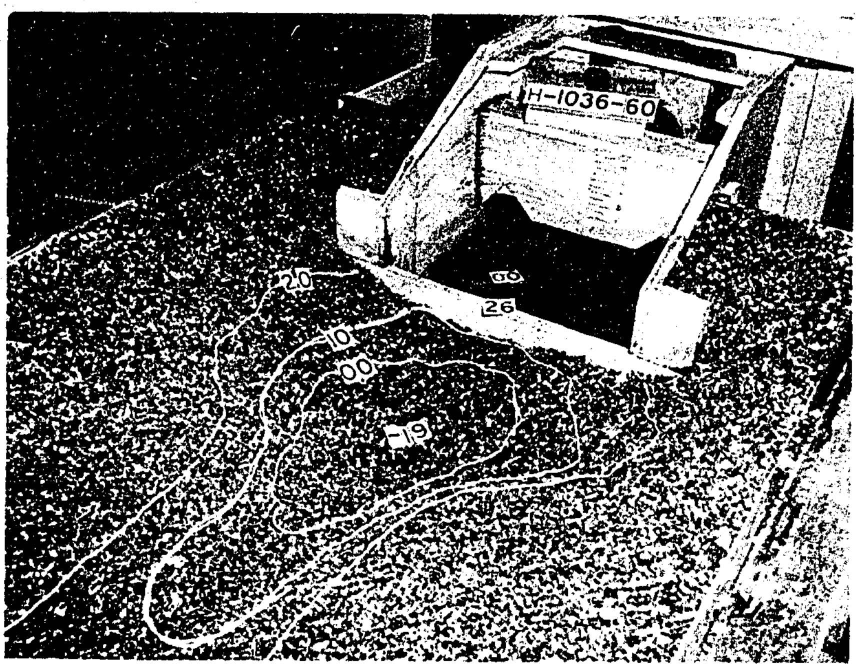
Hydraulic model discharging maximum discharge
under similar conditions of head and tailwater.

MODEL-PROTOTYPE COMPARISON
NORTH BRANCH DAM - PICACHO ARROYO CONTROL

FIGURE 7



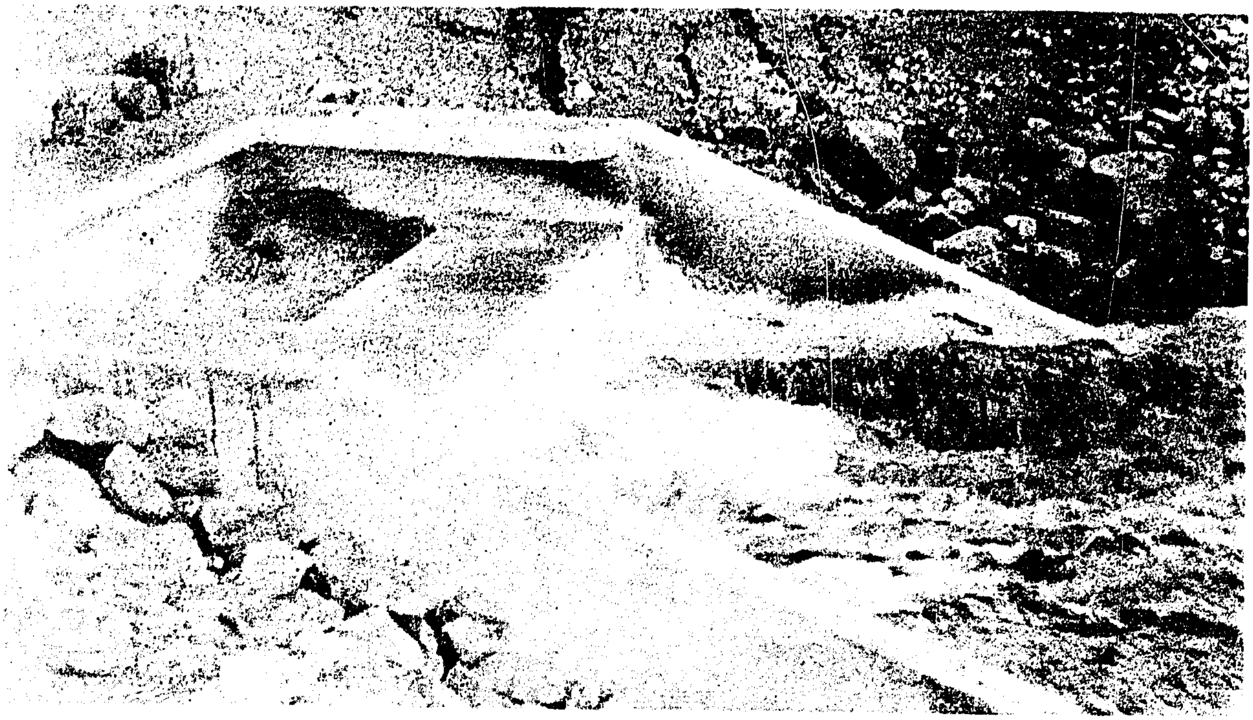
Scour below North Branch Dam outlet works following flood of August 20, 1954. Evidence indicates undersize rip-rap.



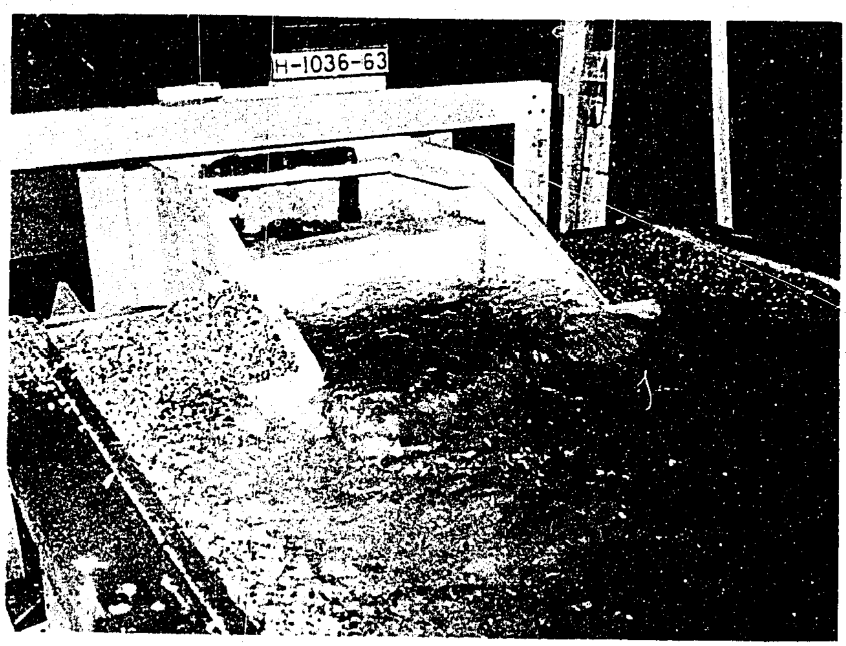
Hydraulic model indicates erosion similar to prototype when rip-rap size is inadequate.

MODEL-PROTOTYPE COMPARISON
PICACHO ARROYO CONTROL

FIGURE 8



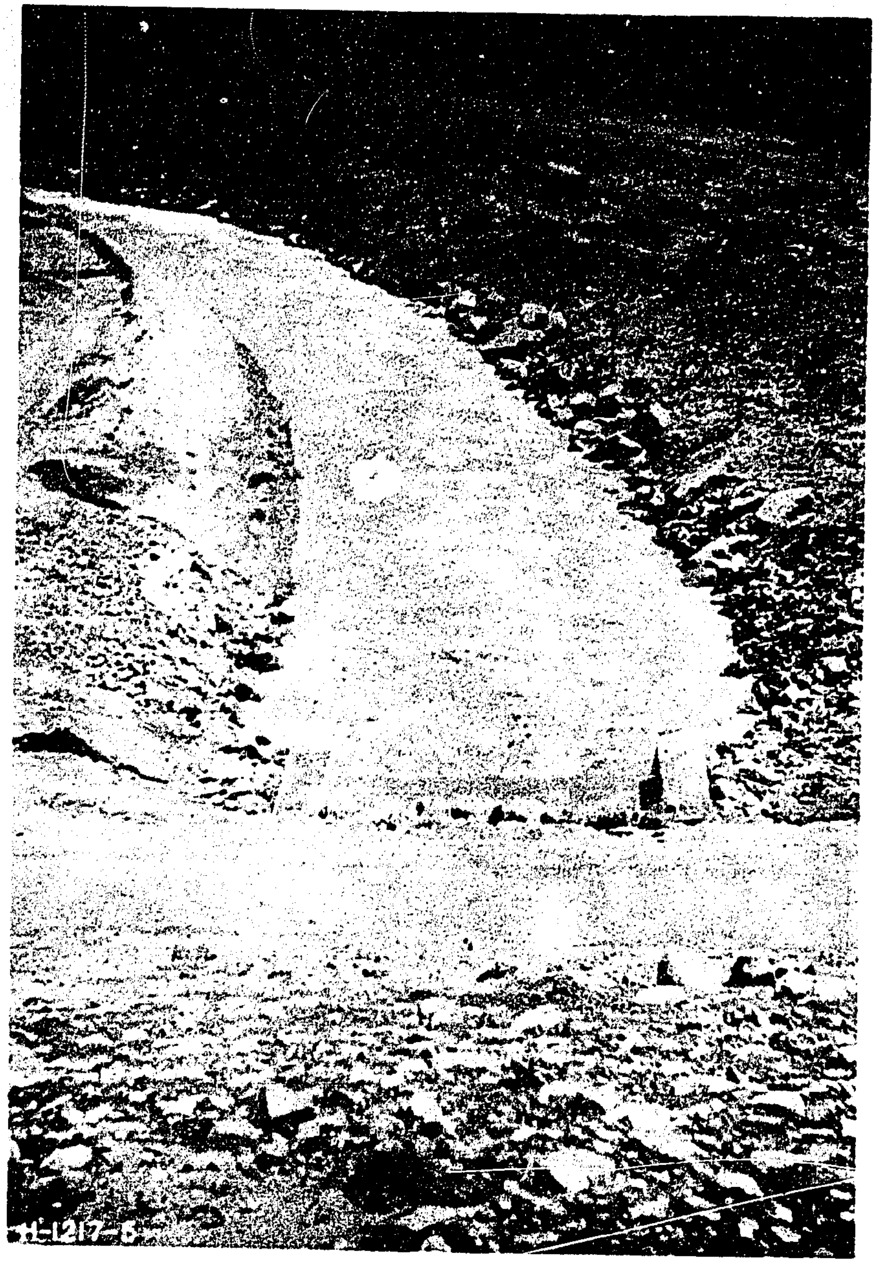
South Dam outlet works structure discharging 130 second-feet (80 percent of maximum).



Flow appearance in model for the same conditions. Note similarity both upstream and downstream from vertical baffle.

MODEL-PROTOTYPE COMPARISON
PICACHO SOUTH DAM

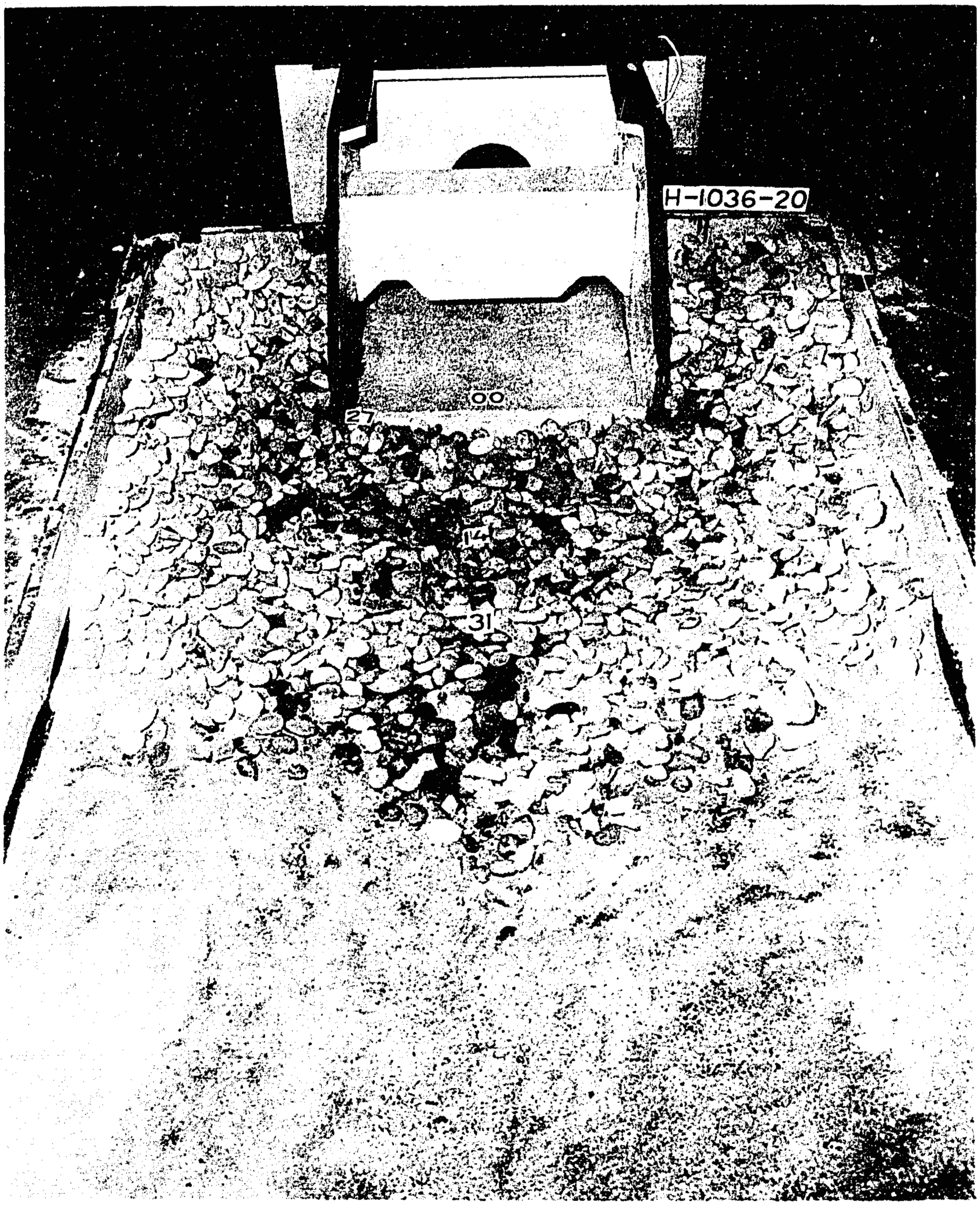
FIGURE 9



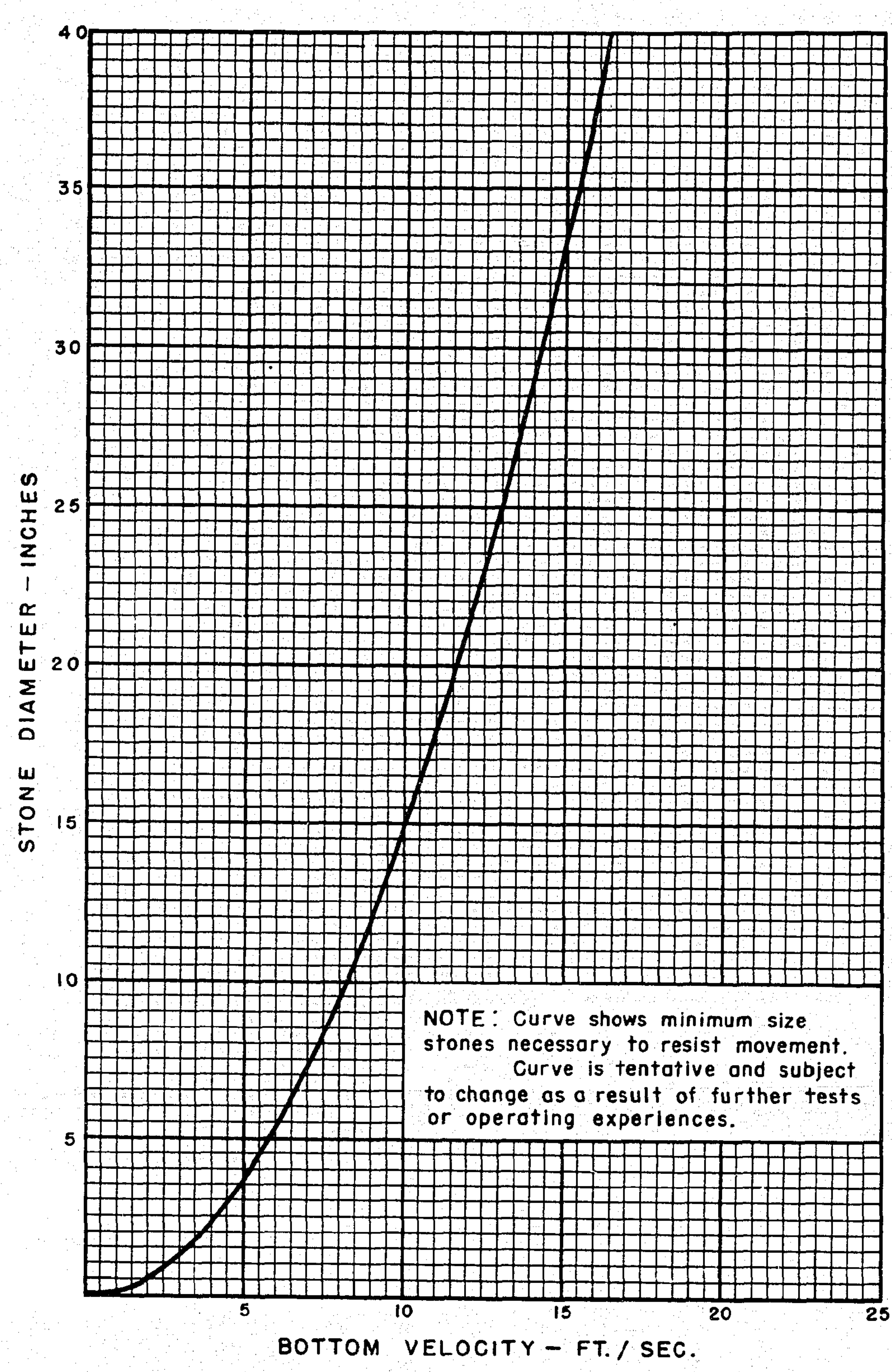
Flow conditions downstream from South Dam outlet works is entirely satisfactory. There was no disturbance or loss of riprap. Discharge 130 second-feet.

PICACHO SOUTH DAM OUTLET WORKS

FIGURE 10



Hydraulic model tests using 9 to 18 inch diameter (equivalent) stones shows some movement of riprap.



TENTATIVE CURVE TO AID IN DETERMING RIPRAP SIZES

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